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A review of islanding detection methods for microgrid

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ABSTRACT

Renewable energy generation is considered as an important approach to solve energy and environment problems in the future. Distributed generation technique is a primary way to utilize renewable energy. Microgrid integrated with different kinds of distributed resources can improve energy efficiency and reduce the negative impact on power grid. Microgrid may operate in grid-connected or islanding mode, running on quite different strategies. Effective islanding detection methods are indispensable to realize optimal operation of microgrid. In this paper, performance indices and critical technique problems are discussed. Islanding detection methods are also classified. The paper aims to discuss the improvement of several performance indices, including non-detection zone (NDZ), detection time, error detection ratio and power quality, to evaluate different detection methods. Effectiveness in multiple-inverter cases is also analyzed. According to the comparison upon the advantages and disadvantages of each method, the applicability is discussed, which may provide a reference for researchers to select islanding detection methods.

Contents

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1. Introduction

In recent years, renewable energy generation techniques have been intensively concerned and developed. Comparing with fossil energy, renewable energy produces less greenhouse gases [1]. Distributed generation (DG), as a primary way to use renewable energy, is effective. With microgrid, these different resources can be integrated as a hybrid energy system, providing electric power with optional cooling or heating [2,3]. Efficiency of renewable energy is significantly developed. In addition, distributed generation techniques are promoted in microgrid. DG connected to the main grid directly has a great negative impact because most of the distributed resources are intermittent. Distributed generations are complementary because they can support each other in the microgrid. On one hand, microgrid can mitigate negative impact to the main grid by these complementarities. On the other hand, various kinds of distributed resources, controllable load and general load can be integrated, reducing dependence on main grid. Therefore, microgrid is widely favored and rapidly developed. In other words, microgrid is a critical path for the sustainable energy development.

Strategies are different when microgrid operates in grid-connected or islanding mode. In the case of islanding mode, to provide reliable power supply or supply parts of special loads under this condition is priority. In grid-connected mode, the objective is optimal economical operation. Therefore, detecting operation condition in time is a premise to optimize control in microgrid. Islanding can be divided into planned islanding and unplanned islanding [4]. Planned islanding is that microgrids still supply electric power to local load reliably when they are disconnected from main grid. It is a controllable operation mode. Unplanned islanding is an undesired event due to line tripping, equipment failure, human errors and so on, with microgrids disconnected from main grid [5,6]. Unplanned islanding is an uncontrollable operation mode which happens occasionally, and the scope of islanding is not determined, thus affecting security of microgrid.

In the paper, the features to evaluate performance of islanding detection methods (IDMs) are discussed, and critical problems to improve performance are presented. IDMs are also classified in this paper. In Section 2, indices of IDMs performance are discussed and critical problems are illustrated. Section 3 discusses advantages, disadvantages as well as applicability of IDMs. Main IDMs are also classified in this part. Section 4 compares performance among different methods, and improvements of IDMs performance indices are described in this part.

2. IDMs performance indices and critical technical problems

Whether islanding can be detected accurately, timely and effectively is largely determined by the performance of IDMs. These indices consist of non-detection zone, detection time, error detection ratio and power quality.

2.1. Non-detection zone

Non-detection zone is the main reason why IDMs fail to detect islanding. It should be summarized in different ways according to different categories of IDMs. NDZ of methods based on monitoring voltage, frequency or phase deviation is often described in power mismatch space. NDZ of methods based on disturbance injection is usually described in load parameter space.

2.1.1. Power mismatch space

Variation of voltage and frequency at a point of common coupling (PCC) is related with power mismatch between DG power output and load consumption when microgrid operates in islanding condition. Especially, in the condition that DG power output and load are almost balanced, power mismatches ΔP and ΔQ are nearly equal to zero. The extent of the variation of voltage or frequency is not enough to detect islanding when microgrid disconnects from grid [7]. The range of power mismatches ΔP and ΔQ, which cannot cause voltage or frequency exceeding normal limit to detect islanding, is NDZ.

NDZ in power mismatch space is shown as [8]

$$\left(\frac{V}{V_{\max}}\right)^2 - 1 \le \frac{\Delta P}{P} \le \left(\frac{V}{V_{\min}}\right)^2 - 1 \tag{1}$$

$$Q\left(1-\left(\frac{f}{f_{\min}}\right)^2\right) \le \frac{\Delta Q}{P} \le Q\left(1-\left(\frac{f}{f_{\max}}\right)^2\right) \tag{2}$$

where $V_{\max}$ and $V_{\min}$ are the maximum and minimum voltages allowed in microgrid respectively, $f_{\max}$ and $f_{\min}$ are the maximum

and minimum frequencies respectively, V is the rated voltage, P is the rated active power, and Q is the quality factor.

2.1.2. Load parameter space

NDZ in parameter space is defined as

$$F_1(cf, K, Q) < \Delta C_{norm} < F_2(cf, K, Q) \tag{3}$$

where cf is the chopping fraction, K is the accelerating gain, Q is the quality factor and ΔC_{norm} is the resonate capacitance in the range of NDZ.

Ropp et al. [7] proposed the $L \times C_{norm}$ axis to describe NDZ in load parameter space, where L is the load inductance and C_{norm} is the normalized capacitance ($C_{norm} = C/C_{res}$, C_{res} is the capacitance that resonates with the load inductance in grid line frequency). In this method, real power between DG and load is assumed to be matched and thus load resistance is determined. Then mapping of NDZ could be described in the $L \times C_{norm}$ axis.

Lopes et al. [9] utilized an alternative load parameter space based on the $Q \times f_0$ axis to describe NDZ, where f_0 is the load resonate frequency. The main advantage of this method with respect to L versus C_{norm} is that it does not plot different curves to analyze NDZ with different resistive loads. The increase in R means the increase in Q, for a given set of L and C loads.

2.2. Detection time

Detection time is the duration from the beginning of microgrid disconnecting from main grid to the end of detecting islanding by IDMs, which is defined as

$$\Delta T = T_{IDM} - T_{trip} \tag{4}$$

where ΔT is the run-on time, T_{IDM} is the moment to detect islanding, and T_{trip} is the moment microgrid disconnects from the grid.

2.3. Error detection ratio

Error detection means that IDMs detect false in islanding when microgrid is still connected to grid. Error detection is mainly caused by load switching or other disturbance, leading measurement parameters to exceed normal limit [10]. The ratio can be defined as the ratio of error detection times to total detection times by IDMs.

$$E = \frac{N_{error}}{N_{error} + N_{correct}} \tag{5}$$

where E is the error detection ratio, N_{error} is the times of error detection, and $N_{correct}$ is the times of correct detection.

2.4. Power quality

Methods based on injecting disturbance can significantly reduce NDZ when detecting islanding. However, it is inevitable for injecting disturbance to distort power output and deteriorate power quality. Power quality is an important index when selecting IDMs.

2.5. Critical technical problems

IDMs have many critical technical problems in improving performance. Methods based on whether detection parameters exceed the threshold caused by power mismatch are hard to eliminate NDZ. Their detection speed is associated with power mismatch, making it hard to predict. Methods based on disturbance injection are inevitable to degrade power quality.

On the other hand, the improvements of different performance indices have many difficult problems that they might be restricted by each other. For example, reducing threshold of normal range could accelerate detection speed, but it becomes easier for detection parameters to exceed threshold in the case of load switching or system transient, increasing error detection ratio. On the contrary, if threshold is set too large, NDZ would become larger and detection speed might become slow despite error detection ratio decreasing. For IDMs based on disturbance injection, reducing NDZ and simultaneously upgrading power quality is in dilemma. By injecting larger distorted disturbance or increasing accelerating gain of the feedback, the size of NDZ could be reduced, but it seriously deteriorates power quality.

It is important to fully consider microgrid's practical operation, with all the key performance indices taken into account. In the case that microgrids are connected to the same PCC in parallel, measurement parameters of some IDMs might cancel out each other because of deviating in different directions, decreasing IDMs' effect or even making it fail to detect islanding. With the development of microgrid, its structure and operation would become more complicated, so IDMs, which can coordinate every performance index to reach a balance, will be widely applied in the future.

3. Islanding detection methods

Islanding detection methods are generally divided into local and remote methods as shown in Fig. 1 [6,11–15]. Local methods are based on measurement of some parameters or variables on the microgrid side, including passive methods and active methods. Passive methods directly monitor parameters or variables including voltage, current, frequency and phase to detect islanding. Active methods intentionally inject a disturbance to detect whether it affects voltage, frequency, power or impedance parameters. Remote methods are based on the communication between microgrid and main grid to monitor breakers immediately. Remote methods present small or even no NDZ, which have no impact on power quality. Remote methods are very effective in multiple-inverter systems, but they need large amount of investment. It is not economic in small systems.

3.1. Passive methods

3.1.1. Voltage and current harmonics detection (HD)

This method is based on the measurement of total harmonic distortion (THD) at PCC to detect islanding when THD exceeds the threshold. Under normal conditions, when the microgrid is connected to main grid, PCC voltage is a standard sine wave, and thus load-generated harmonics are negligible. Because the grid impedance is very small, the harmonics produced by the inverter are transmitted to the grid without causing distortion at PCC. When a microgrid is running on islanding condition, the current harmonics produced by the inverter are transmitted to the load and hysteresis effect of transformer will further aggravate harmonic distortion at PCC, which is able to detect islanding [12,13,16].

This method has an advantage that its effectiveness does not change when multiple DGs are connected to the same PCC in parallel, and is easy to implement. The detection time is about 45 ms under a fast detection speed and a wide range of situations [11]. However, the threshold is difficult to select for this method because grid disturbance is easy to cause error detection. This method is prone to fail if NDZ is large for loads with a large quality factor Q. Q is defined in [7,17], as Eq. (6). Thus the harmonic detection method is difficult to apply in small single systems.

$$Q = R\sqrt{\frac{C}{L}} \tag{6}$$

Q is equal to 2π times the ratio of the maximum stored energy at the resonant frequency to the energy dissipated of a cycle at

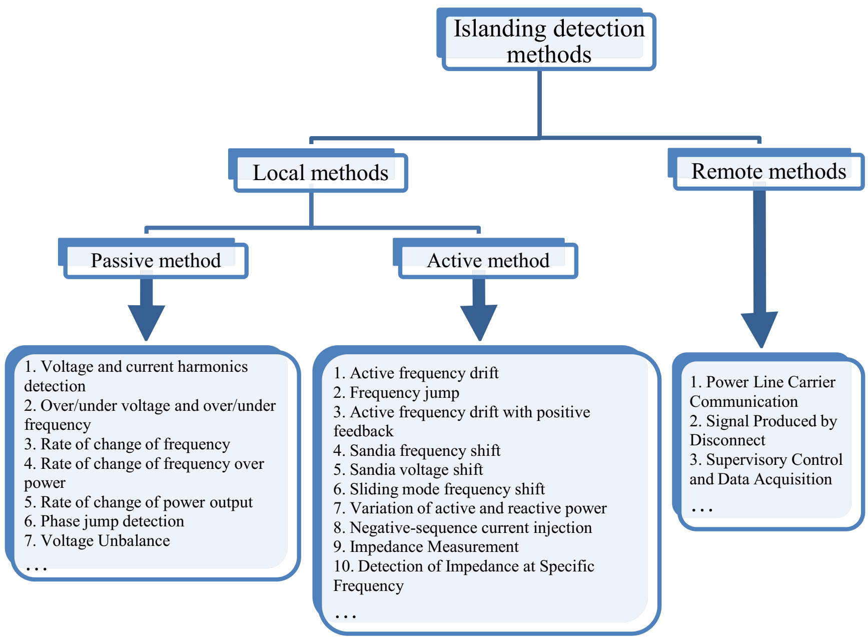

Fig. 1. Classification of islanding detection methods.

that frequency. When the resonant frequency of the load closes to the grid rated frequency, such as 50 Hz or so, the value of Q has great influences on the size of NDZ and detection accuracy.

3.1.2. Over/under voltage and over/under frequency (OUV/OUF)

This technique is based on setting an allowable range for voltage and frequency. Inverters will disconnect to stop supplying power to the load if the voltage or frequency at PCC exceeds thresholds. The frequency or voltage deviation after microgrid disconnection is mainly due to the power mismatch between distributed generation and loads in microgrid, at PCC:

$$\Delta P = P_{load} - P_{DG} \tag{7}$$

$$\Delta Q = Q_{load} - Q_{DG} \tag{8}$$

In grid-connected operation, ΔP and ΔQ will be injected from main grid to keep the balance of active and reactive power. When islanding occurs, in order to meet the active and reactive power balance, its voltage and frequency will drift until $\Delta P = 0$ and $\Delta Q = 0$. Thus OUV/OUF can detect islanding by detecting voltage and frequency deviations [11–13,16].

This method, with low cost, has no impact on power quality. Weaknesses are those that NDZ is relatively large and detection time is difficult to predict. The run-on time is from 4 ms to 2 s, even more than 2 s [18]. Detection speed is related to the power mismatch between DG and loads. Therefore, this method is suitable for microgrid with some power imbalance.

3.1.3. Rate of change of frequency (ROCOF)

When the microgrid is disconnected from main grid with a power mismatch, the frequency will change. With the value of df/dt measured over a few cycles, the islanding can be detected and inverters shut down [19,20], if it exceeds a setting threshold.

ROCOF is more sensitive than OUV/OUF, and its detection speed is faster. If the power mismatch between DG and load is large, this method is highly reliable and timely. The detection time is up to 24 ms [19]. Even when power between DG and load is in balance, any disturbance produced by load changes could break this balance, leading to frequency changes to detect islanding. The weaknesses of ROCOF are those that it is sensitive to load switching and fluctuation, which may lead to error detection and make the selection of threshold difficult. This method cannot distinguish whether the frequency change is caused by islanding or load changes [21]. Thus ROCOF is suitable for loads with less fluctuation.

3.1.4. Rate of change of frequency over power (ROCOFOP)

This method is based on the measurement of the value of $\partial f/\partial P_L$, an index to determine whether microgrid is running on islanding condition, where P_L is the load power. This method has higher reliability, lower error detection ratio and its NDZ is smaller than ROCOF. It can detect islanding more effectively when the power mismatch is small between the DG and load. Detection time of this method is about 100 ms [22]. Compared with ROCOF, this method could be applied in wider range of situations. It can detect islanding effectively in microgrid with small power imbalance [20,22].

3.1.5. Rate of change of power output (ROCOP)

Principle of this method is the detection of the changes in the DG power output (dP/dt), because loss of grid generally produces load changes. For the same rate of load change, dP/dt measured when microgrid is islanded will be much greater than dP/dt measured before microgrid is islanded. The value of power change is measured over a few sample cycles. When the integrated change exceeds the threshold value, the DG will be disconnected to stop supplying power to the load [11].

The detection time of this method is between 24 ms and 26 ms [19]. Compared with OUF, its detection speed is not affected when the power mismatch between DG and load is small. Another advantage of this method is that it is able to quickly detect unsynchronized reclosing of the utility supply to the DG to ensure stable operation of power system. This method still has NDZ in the condition of power balance. But with the increasing of power imbalance, the method will become more effective to detect islanding.

3.1.6. Phase jump detection (PJD)

This method is based on monitoring the phase jump between the inverter's terminal voltage and current. When microgrid is

under normal operation, by using PLL to detect zero crossing of voltage, the inverter's current will be synchronized with the voltage at PCC. In islanding operation, the inverter's output current remains unchanged, because phase-locked loop can only work at the zero crossings of voltage. Due to load phase angle, the voltage will have a sudden "jump". If the phase difference exceeds the setting threshold, the method can determine the islanding [12].

Major strengths of this method are the ease of its implementation and fast detection speed, and the detection time of this method is usually between 10 ms and 20 ms [23]. PJD does not affect the power quality. Effectiveness of this method is not reduced in the case of multiple inverters. Disadvantage of this method is that it is difficult to choose thresholds. Because of the load switching, particularly motor load, which increases the difficulty in setting the thresholds for PJD, an error will be caused in the detection of islanding. Similarly, if local loads are not producing sufficient phase error, it is difficult to detect islanding by using this method. Thus PJD is suitable for microgrids in the situations where load phase angle is enough and load switching is not frequent.

3.1.7. Voltage unbalance (VU)

Due to the topology changes of the networks after the microgrid disconnected from main grid, the voltage unbalance of DG output varies. If the unbalance of three-phase output voltage of the DG exceeds the setting threshold, it will determine an islanding operation [20]. The voltage unbalance at the time t is defined as

$$VU_t = \frac{NS_t}{PS_t} \tag{9}$$

where NS_t and PS_t are the amplitudes of negative and positive sequence of voltage at the time t, respectively.

The detection time is about 53 ms [24]. In the situations of variation caused by normal loads, this method is hard to cause error detection and it is not sensitive to the system disturbance. The disadvantage of this method is that the extraction of negative sequence voltage component is affected by harmonics, increasing the difficulty in calculating thresholds. This method is better to be applied in systems with load fluctuations, such as motor starting and frequent capacitor banks switching.

3.2. Active methods

3.2.1. Active frequency drift (AFD)

This method is based on slightly distorting the current waveform injected into PCC by the inverter. When connected to the grid, the voltage and frequency of PCC will not change owing to the stability of main grid, and the frequency of the inverter's output current will not change after a phase-locked loop, either. When a grid disconnection occurs, because of distortion of the injected current waveform, the zero crossing of the voltage occurs sooner than expected, thus giving rise to a phase error between the voltage and the inverter's output current. It makes the inverter to drift frequency of output current to eliminate the phase error. The voltage response of this current frequency drift causes an earlier zero crossing than expected again, making the inverter's output current to drift its frequency until the voltage frequency measured in PCC exceeds the threshold of OUF and then the islanding is detected [12].

The major parameter describing the distortion of the inverter's injected current is the chopping fraction, which is defined in [25,26], as the following equation.

$$cf = \frac{2t_z}{T_{Vutil}} \tag{10}$$

where t_z is the dead time and T_{Vutil} is the period of the voltage.

The strengths of AFD are that it is easy to implement and has a small NDZ, and particularly, there is no NDZ in resistance load with the detection time within 2 s [11]. The weakness is that in multiple inverters case, the method may fail to detect islanding because of inverters in different deviations of frequency bias. With the injected current distorting more heavily, the power quality of inverters output will degrade more quickly. Load parameters play a great role to the effectiveness of the method. If the load is not resistance, the detection time and the NDZ will increase with higher value of Q. Therefore, AFD is the best for the islanding detection of microgrid which is just made up of resistive loads and without multiple inverters.

3.2.2. Frequency jump (FJ)

FJ is a modification of AFD, which also inserts dead zones into current waveform, but not into each cycle, for example, one dead zone in every 3 cycles, instead. When the microgrid is connected to main grid, the waveform of voltage in PCC, which is imposed by the grid despite inverter's current is distorted, is not distorted. When disconnected from main grid, islanding can be detected by a variation in voltage frequency [7,8,11].

FJ is very effective in detecting microgrid without multiple inverters in parallel; the disadvantage is that, like AFD, the detecting effectiveness will be reduced when multiple inverters are in parallel.

3.2.3. Active frequency drift with positive feedback (AFDPF)

To overcome the weakness of AFD in multiple inverters and reduce NDZ, AFDPF utilizes a positive feedback to increase chopping fraction to accelerate frequency deviation, detecting islanding more effectively.

$$cf_k = cf_{k-1} + F(\Delta\omega_k) \tag{11}$$

where cf_k and cf_{k-1} are the chopping fractions of the kth and k-1th cycles, respectively. Where ω_k is the frequency of the kth cycle, $\Delta\omega_k = \omega_{k-1} - \omega_0$, F is usually a linear function. The value of cf in AFDPF can be positive or negative. No matter if frequency drift is upward or downward, this method can reinforce the frequency drift instead of counteracting it, overcoming the impact of the load parameters [26]. The performance has been improved compared to AFD, greatly reducing the NDZ. Its disadvantages are that it affects the power quality slightly, and still has NDZ for loads with high quality factor.

3.2.4. Sandia frequency shift (SFS)

As an extension of AFD, a positive feedback is applied for the frequency of inverter's voltage, whose chopping fraction is [12,25,27]

$$cf = cf_0 + K(f_{PCC} - f_{grid}) \tag{12}$$

where cf_0 is the chopping factor with no deviation in frequency, K is the accelerating gain, f_{PCC} is the voltage frequency in PCC, and f_{grid} is the frequency of the grid.

When connected to main grid, the method attempts to change the voltage frequency of PCC but it is prevented by main grid. When disconnected from main grid, the chopping fraction increases with the increase of f_{PCC}. Therefore, the frequency of the inverter also increases, and all these processes will continue to reinforce the frequency shift to detect the islanding effectively. The detection time of SFS is within 0.5 s, and it even can detect islanding in 7 cycles [17]. This method, compared with another active methods, has the smallest NDZ. In addition, SFS is very effective to compromise the detecting efficiency, power quality as well as the impact on system transient response.

3.2.5. Sandia voltage shift (SVS)

Sandia voltage shift is similar to SFS in principle. By applying a positive feedback to the amplitude of voltage in PCC, the inverter changes its current output and power output. When connected to main grid, the amplitude of voltage is not affected by power change, whereas without the support of main grid, power output changes can accelerate the voltage drift to detect islanding [13,17,27].

SVS is easy to implement, and it has the same efficiency as the SFS method which is based on positive feedback. The primary weakness of SVS is that it slightly degrades power quality. Secondly, because of changing the inverter's output power, it affects the maximum power point tracking algorithm of the inverter, reducing the inverter's operation efficiency [12,13].

3.2.6. Sliding mode frequency shift (SMS)

SMS utilizes positive feedback to change the voltage phase of PCC, monitoring frequency deviation to detect islanding. In SMS, the current–voltage phase angle of the inverter is set as [9,20,28]

$$\theta = \theta_m \sin\left(\frac{\pi}{2}\frac{f^{k-1} - f_n}{f_m - f_n}\right) \tag{13}$$

where θ_m is the maximum phase angle at the frequency f_m, f_n is the rated frequency, and f^{k-1} is the frequency of previous cycle.

When the microgrid operates normally, its power factor operates with main grid. The phase angle between the inverter current and the PCC voltage is controlled to be zero or very close to it. When disconnected from main grid, the phase angle of load and the frequency will vary along with the SMS curve, and thus islanding can be detected if frequency variation exceeds the threshold. The detection time of this method is about 0.4 s [9]. Advantages of SMS are that it is easy to implement and has smaller NDZ than general active methods. Moreover, SMS is highly effective in multiple-inverter systems. Disadvantages of the method are that it reduces the grid power quality and has certain impacts on system transient stability.

3.2.7. Variation of active and reactive power

This method varies the output power injected by inverter and monitors the variation in voltage amplitude and frequency to detect islanding. For example, when a microgrid is islanding, the active power of DG will flow into the load. To balance the active power between DG and the load, the voltage variation must satisfy [27]:

$$P_{DG} = P_{load} = \frac{V^2}{R} \tag{14}$$

Islanding can be detected when the voltage exceeds the threshold of OUV. In a similar way, the disturbance of reactive power will affect the variation in frequency, and islanding can be detected by measuring whether the frequency exceeds the threshold or not [13].

The detection time of this method is between 0.3 s and 0.75 s, and its advantages are that it is easy to implement, and has a small NDZ with less investment [25]. The greatest weakness is that it will lead to erroneous detect when multiple inverters are parallel at the same PCC. The method continuously varies power output of inverters, affecting the grid power quality and transient stability greatly. Variation of active and reactive power is generally applied in islanding detection for microgrid without multiple inverters.

3.2.8. Negative-sequence current injection

This method injects negative-sequence current into a three-phase voltage-sourced converter, monitoring the negative-sequence voltage at PCC to detect islanding. When connected to the grid, because main grid has low impedance, injected negative-sequence current will entirely flow into the grid without impacting the voltage of PCC. When the microgrid is islanding, injected current will flow into the local load, contributing to an unbalance in the voltage of PCC and detecting islanding when the voltage unbalance exceeds the threshold.

This method can detect islanding event with 3.5 cycles, 60 ms, a very short detection time compared to another active method. Its advantages are that it is not sensitive to load change, presents no NDZ and the accuracy is higher than detecting positive-sequence voltage [29].

3.2.9. Impedance measurement (IM)

Impedance measurement is a method that changes the amplitude of inverter output current in general. When disconnected from main grid, the voltage varies as a result of perturbation in current. Variation monitored by calculating dv/di as equivalent impedance seen from the inverter can be used to detect islanding [13,30].

The detection time of the IM method is between 0.77 s and 0.95 s [11], and main advantage of this method is that it has extremely small NDZ for single DG system. However, this method also has many disadvantages. For example, the detection efficiency will decrease in multiple-inverter cases, unless all inverters operate synchronously. The impedance threshold is also hard to set because it requires exact value of grid impedance. So, this method is difficult to practically apply.

3.2.10. Detection of impedance at specific frequency

This method is a special case of harmonic detection method. Specific frequency harmonics are injected by inverters. When microgrid operates in grid-connected mode, the harmonic current will flow into grid without causing an abnormal voltage in PCC, for grid impedance is much lower than load impedance. When microgrid disconnects from grid, the harmonic current will completely flow into local load, producing a harmonic voltage in PCC if the load is linear, and islanding can be detected while harmonic voltage is large enough.

The strength of this method is similar to harmonics detection. The weakness is that it is easy to cause equipments misoperation, such as transformers, unless harmonic amplitude is small. Error islanding detection may happen if the same harmonic current is injected by multiple inverters. So this method is not suitable for multiple-inverter cases [12].

3.3. Remote methods

3.3.1. Power line carrier communication (PLCC)

Transmitters are set at grid side in the PLCC method, which can produce communication signal along with power line through PLCC system. And the DG side is equipped with receiver. If PLCC signal is interrupted, it indicates that microgrid is islanding [31].

The signal period of PLCC is designed with four consecutive cycles. Islanding can be detected if signal disappears in three consecutive periods. Thus the detection time is about 200 ms [32]. There is no NDZ within the range of normal loads. The method does not degrade power quality and has no impact on grid transient response. It is proved to be highly effective in multiple-inverter system. Furthermore, this method only uses PLCC signal which has existed in power grid to detect islanding. But the transmitter is expensive, and would not be economical in low-density DG systems. So, this method is applied in the microgrid with high-density DG systems.

3.3.2. Signal produced by disconnect (SPD)

This method is similar to PLCC, detecting islanding according to signal transmission between inverters of DG and external power grid. The difference between them is that signal transmission is based on microwave, telephone line and others forms. This method also utilizes the consecutive carrier signal, to prevent the failure caused by generator, channel or receiver [11–13].

SPD has no NDZ, and it allows additional control to DG by main grid, coordinating between DG and grid power source which would be beneficial to black-start. The system startup characteristics also can be improved by this coordination. The disadvantage of the SPD method is that it needs large amount of investment. If telephone line is used for signal transmission, the cost of communication wiring needs to be added and communication protocol should be set up. If microwave is used to transmit signal, repeaters are needed to install.

3.3.3. Supervisory control and data acquisition (SCADA)

This method measures the auxiliary contacts of grid circuit breakers, monitoring the state of main grid. In the case of islanding operation, SCADA system will send signals to corresponding range of DG, and thus the state of circuit breakers is transmitted to DG by SCADA system [11–13].

The advantage of this method is similar to SPD that it is able to take additional control of DG. If the system installation is proper and communication is available, NDZ can be eliminated and operation efficiency can be improved. The disadvantage of this method is that the detection speed is rather slow, especially under the condition of a busy system. The investment is increased for requiring separate instrument and communication link in multiple-inverter case. This method requires complex installation and certification, which is not suitable for small-scale system.

4. Analysis of IDMs performances

4.1. Non-detection zone

With the characteristics of NDZ summarized, it is effective to present the applicability of each IDMs and factors which affect NDZ. Furthermore, performance of IDMs can be upgraded by comparing NDZ of different methods. With the increasing of chopping factor or accelerating gain, the size of NDZ can be reduced. Moreover, methods based on positive feedback can reinforce frequency deviation to reduce NDZ more effectively than frequency drift methods.

4.1.1. Power mismatch space

OUV/OUF usually has a large NDZ. Jones et al. [18] proposed that this method is more sensitive to reactive power mismatch. In NDZ, the range of ΔQ is smaller than that of ΔP. ROCOP directly monitors power output changes, reducing NDZ. ROCOF measures the value of df/dt. Though in the case that power is in balance, any subsequent load change would enable this method to detect islanding because it is very sensitive [20]. ROCOFOP reduces NDZ and provides more reliable detection on the basis of ROCOF [22].

The $\Delta P \times \Delta Q$ axis can only map NDZ of a specific load, because NDZ maps are meaningless when load parameters have changed. Power mismatch method can only describe NDZ of passive methods based on monitoring whether voltage or frequency exceeds normal range, which cannot be utilized in active method.

4.1.2. L versus C_{norm} parameter space

Ropp et al. [26] discussed NDZ of AFD and AFDPF methods. According to the discussion, NDZ would reduce with the increase of chopping fraction. Moreover, AFDPF has a smaller NDZ than AFD and the range of C_{norm} in NDZ is significantly reduced with a given inductance. Ropp et al. [7] compared NDZ of SMS and AFD methods. The NDZ map of SMS shows that its NDZ is similar with that of AFD. Moreover, if L is above a certain threshold, SMS has no NDZ. SFS has a smallest NDZ. Not only NDZ is narrower than that of AFD and SMS under the condition of small L and large C values, but also the size of NDZ reduces faster when load inductance is increased. The threshold L without NDZ is smaller than the one in the SMS method [7].

Load parameter space ignores effect of load resistance when applied to describe the map of NDZ. With the increasing of R, size of NDZ might become wider by increased load quality factor. Load parameter space cannot reflect the influence by Q values.

4.1.3. Quality factor versus resonate frequency parameter space

Lopes et al. [9] showed the NDZ of the AFD method with different chopping fractions, concluding that increasing cf could reduce NDZ. SMS and SFS improved performance to reduce NDZ. Furthermore, SMS and SFS methods could eliminate NDZ for $Q < 2.5$ and $Q < 4.8$ respectively.

4.2. Detection time

Fast detection is a premise for microgrid to have enough time to operate islanding strategy, assuring security and reliability. Passive methods are based on monitoring transient response of parameters including voltage and frequency. Their detection speed is faster than most active methods generally. Run-on time of the OUF/OUV method spans widely, making it difficult to predict. In the case that real power mismatch reaches 40% or reactive power mismatch exceeds 20%, the islanding could be detected in one cycle of disconnection from main grid. However, with the load matching to power generation, run-on time to detect islanding would become longer, even within 2 s [18]. HD and VU could have improvements to detect islanding within 50 ms and ROCOP could reach 24–26 ms [11,19,24]. These methods can also detect islanding faster than OUV/OUF when power becomes matched. PJD and ROCOF are most sensitive and they could detect islanding in 20 ms [19,23].

Active methods which monitor system transient response by injecting a perturbance to detect islanding generally have a longer detection time. Run-on time of AFD is in 2s and it is much affected by Q values. The detection time is improved to 0.77–0.95 s by the IM method [11]. It is further improved by power variation method to 0.3–0.75 s [25]. SMS, SFS and SVS IDMs can detect islanding in 0.5 s in most cases and their detection speed is slightly affected by load quality factor. Even SFS can detect islanding in 7 cycles [9,17]. Negative-current injection method improves detection time in 3.5 cycles with 60 ms [29].

For remote methods like SPD and SCADA which use auxiliary communication ways to transmit signal, detection speed easily becomes slow when the system is busy. Chowdhury et al. [33] proposed that signal through direct communications is about 100–150 ms for fiber-optic or microwave links and 200–300 ms for telephone lines. PLCC utilizes power line to transmit signal and its detection time is about 200 ms.

4.3. Error detection ratio

When setting the normal range of measurement parameters, the scope could not be too large considering size of NDZ. On the other side, it could not be set too narrow because of high error detection ratio. IDMs which are sensitive to load fluctuation generally have higher error detection ratio, selecting a reasonable threshold difficultly. The threshold of the HD method selected must be higher than THD expected in grid voltage and lower than THD produced

Table 1
Summarization of IDMs.

Categories	IDMs	NDZ	Detection time	Error detection rate	Power quality	Effectiveness in multiply-inverter cases	Advantages, disadvantages and applicability
Passive methods	HD	Large with a large value of Q	45 ms	High	No impact	Very effective	Advantages of passive methods are that they have no impact on power quality, and detection speed is fast. Disadvantages are that NDZ is large and error detection rate is higher than active method. Passive methods are usually applied in single DG systems with a certain power imbalance.
	OUV/OUF	Large	From 4 ms to 2 s		No impact		
	ROCOF	Small	24 ms	High	No impact		
	ROCOFOP	Smaller than ROCOF	100 ms	Low	No impact		
	ROCOP	Smaller than OUV/OUF	24–26 ms		No impact		
	PJD		10–20 ms	High	No impact	Not reduced	
	VU		53 ms	Low	No impact		
Active methods	AFD	NDZ increases with increasing of Q	Within 2 s		Degrade	Performance is reduced	Advantages of active methods are that they reduce the size of NDZ and decrease error detection ratio. But they are inevitable to deteriorate power quality. Active methods are usually applied to confirm whether microgrid is islanding. Moreover, effectiveness in multiple DG systems should be concerned.
	FJ	Small			Degrade	Reduced	
	AFDPF	Smaller than AFD			Slightly degrade		
	SFS	Smallest	In 0.5 s	Low	Slightly degrade		
	SVS	Smallest		Low	Slightly degrade		
	SMS	Smaller than AFD	About 0.4 s	Low	Have impact on system transient stability	Highly effective	
	Power variation	Small	0.3 s-0.75 s	High	Degrade power quality and affect system transient stability	Increasing error detection rate	
	Negative -sequence current injection	None	60 ms	Low			
	IM	Small NDZ for single system	0.77 s–0.95 s		Produce harmonics	Reduced	
	Detection of impedance at specific frequency			High	Produce much harmonics	Deteriorate power quality heavily	
Remote methods	PLCC	Without NDZ in range of normal loads	200 ms	None	No impact	Highly effective	Advantages of remote methods are that they have no NDZ, and have no impact on power quality and system transient response. Error detection also can be eliminated. Disadvantages are that remote methods request large amount of investment. Remote methods are usually applied in high-density DG systems.
	SPD	None	100 ms–300 ms	None	No impact	Highly effective	
	SCADA	None	Detection speed is slow if systems are busy	None	No impact	Highly effective	
Hybrid methods	ROCOV and power variation	Small		Low	Small		Hybrid methods are effective to be applied in complex systems. With the combination of methods, it can improve multiple performance indices simultaneously by their compensation.
	VU and SFS, SVS	Very small		None	Reduce negative impact	Effective	
	ROCOF and IM	Small	0.216 s	Low			

during islanding. In reality, there are many occasions, such as power electronic converters that produce harmonics resonated by power system, which may cause THD increasing significantly. Another transient response with a momentary increase in THD also can cause this method to detect false islanding. ROCOF is sensitive to load fluctuation and easy to detect false islanding. ROCOFOP, which monitors $\partial f/\partial P_L$ to detect islanding, decreasing error detection ratio caused by load changing, has an improvement in performance compared with ROCOF. SMS, SFS and SVS are reliable to detect islanding, which are less affected by load changing. Negative current injection method monitors current of the grid line to prevent false trips.

4.4. Power quality

Power variation method seriously deteriorates power quality and has much impact on system transient response, causing voltage flicker and instability. Detection of impedance at the specific frequency method produces much harmonics to increase amplitude of harmonic voltage especially in multiple-inverter cases. AFD decreases power quality along with the increasing of chopping fraction. SFS, SVS and SMS only have slight impact on power quality.

4.5. Effectiveness in multiple-inverter cases

Multiple inverters in parallel which might have impact on IDMs performance should be considered when selecting IDMs in multiple inverters and DG systems. Effectiveness of IM decreases in multiple-inverter cases unless variation introduced by each inverter is synchronized. The reason is that the total current is reduced when more inverters are added, because they might cancel out each other or even make voltage variation undetectable. AFD and FJ must assure that all inverters are in the same direction of frequency bias in order to maintain effectiveness in multiple-inverter cases. Power variation method easily generates false detection of islanding when multiple inverters are connected to same PCC of the grid. SMS and PJD are highly effective in multi-inverter cases.

4.6. Performance improvement by combination of IDMs

Combination of rate of change of voltage (ROCOV) and variation of active power: this hybrid method is based on combination of passive (ROCOV) and active (variation of active power) methods. When microgrids operate in grid-connected mode, only ROCOV is applied to monitor voltage change, which does not deteriorate power quality. The active method is applied only when ROCOV has detected voltage change but cannot identify that the change is caused by islanding or another disturbance. This method can efficiently reduce error detection ratio. Compared with two methods applied separately, the hybrid method can improve performance of power quality and error detection ratio simultaneously [34].

Combination of VU and SFS, SVS: compared with SFS and SVS methods in multiple DGs systems, this hybrid method can reduce negative impact on power system transient response. Compared with VU, this method can efficiently discriminate islanding and load switching, avoiding error detection [35].

Combination of ROCOF and IM: the islanding detection scheme of this hybrid is based on two stages. ROCOF is used as primary protection and IM is the backup. Compared with ROCOF, this method can discriminate islanding and another disturbance, detecting islanding more reliably. Compared with IM, this method can detect islanding satisfactorily for different types of loads in 0.216 s, reducing detection time efficiently [36].

Summarization of IDMs different performance indices, different categories for advantages and disadvantages, and applicability are shown in Table 1. According to the table, some performance indices are not mentioned for several IDMs. The reasons may include firstly, the method to describe map of NDZ is complex, and different methods have different ways to identify NDZ. We can only evaluate or compare those different IDMs whose NDZ are mapped in the same way. For one islanding detection method, variables in definition of NDZ include chopping factor or accelerating gain, which may change in reality. Thus size of NDZ will also change. Secondly, different performance has conflict. For example, NDZ may contradict with error detection ratio for some methods based on whether the measured parameters have exceeded threshold. It makes no sense to improve performance on the one hand while ignoring performance request on the other hand. In further research, it is significant to consider different performance indices comprehensively. Relationships among different indices should be summarized. We can select a suitable islanding detection method effectively which is satisfactory to different performance requests.

5. Conclusions

Several islanding detection methods are presented in this paper. Local methods have been divided into passive and active methods, which are based on the inverter side, whereas in remote methods, IDMs are based on communications between main grid and microgrid. Several significant indices to evaluate performance of IDMs also have been discussed in this paper, including non-detection zone, detection time, error detection ratio and power quality. Effectiveness of IDMs in multiple inverters and multiple DG systems cases is analyzed in this paper. The improvement of IDMs in each performance index is described. Their advantages, disadvantages and applicability are summarized in this paper.

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